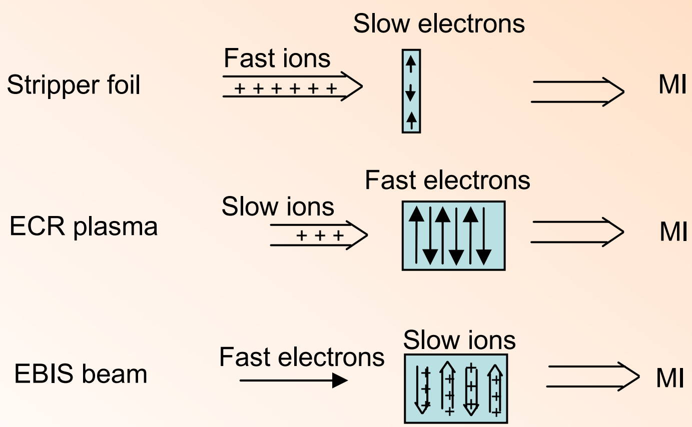
Charge Breeding Techniques



RNB6
Argonne
22-26th September 2003

ISOLDE
CERN

Fredrik Wenander

AB/CERN

History

* Strippers around since ever
* ECRIS CB studies 1993
  (ISN Grenoble for PIAFE)
* EBIS injection tests 1994
  (Stockholm for REX)
* REX-ISOLDE RIB 2001

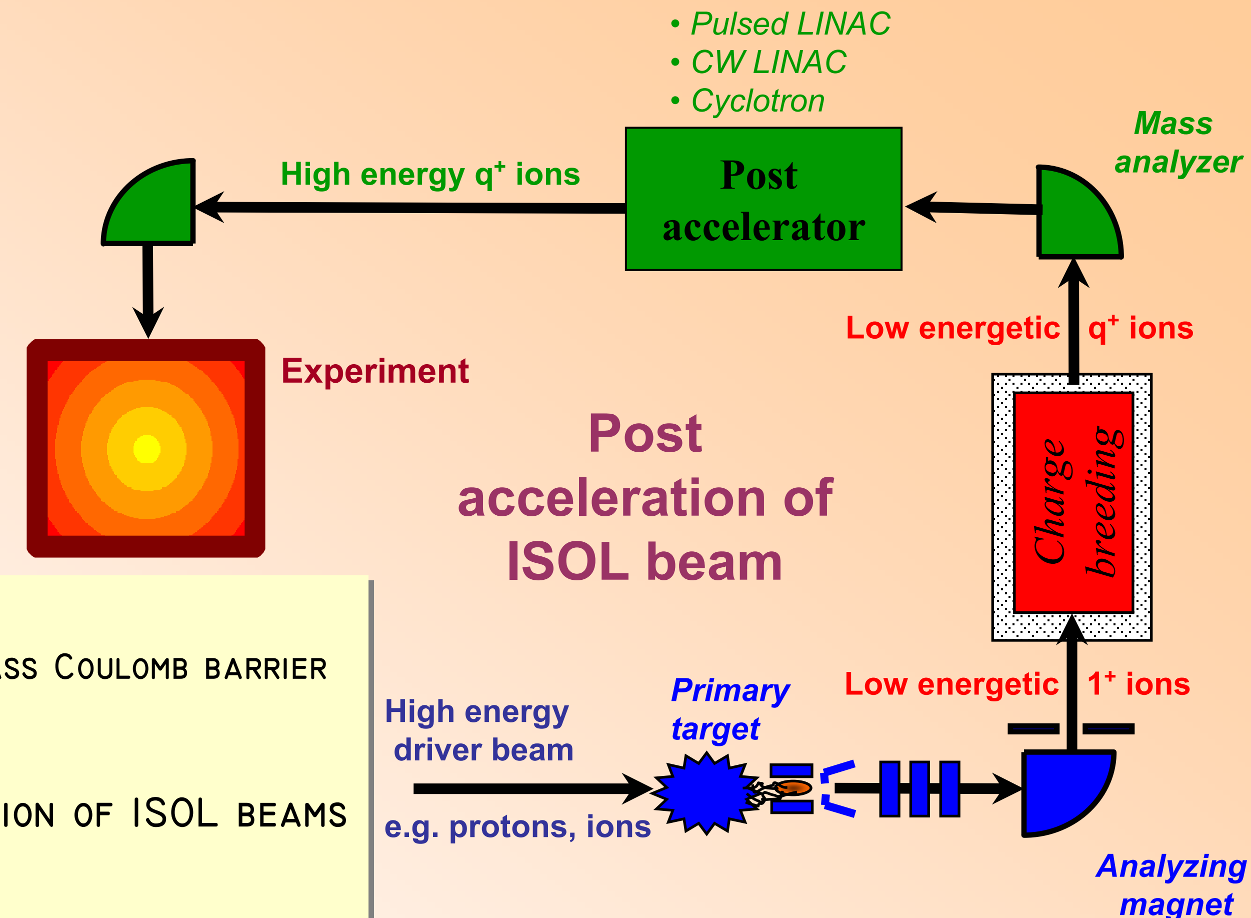
Outline of talk

1. Motivation
2. CB techniques & results
   - Stripper
   - EBIS
   - ECRIS
3. Future development
4. Conclusions

Motivation

Physics case for physicist to motivate

Post acceleration of ISOL beam



Energy request

* Few MeV/u to reach and pass Coulomb barrier
* GeV for beta beams

-> need for post acceleration of ISOL beams

And

Energy $\propto$ q in LINAC; q^2 in cyclotron

Mass-to-charge ratio (A/Q) < 1/9

The idea

Charge breed ($1^+ \rightarrow n^+$) low-energy ions

Simplicity(?)

Efficiency(?)

Compactness (shorter/simpler/cheaper LINAC)

Brute force

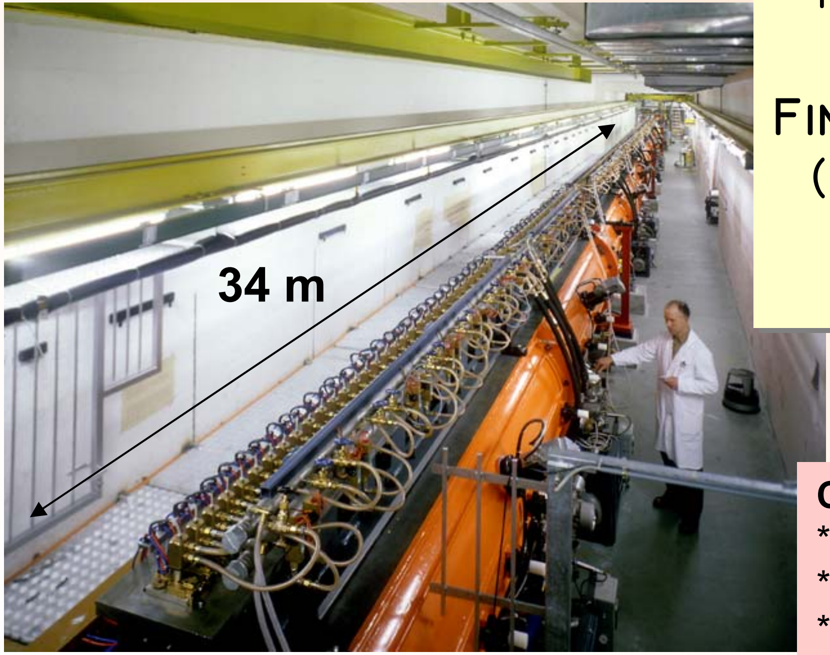
How long would a I^+ linac be?

* W_{nucl} [MeV/u]=$E_{acceleration}$ [V/m] * q/A [e/u] * L [m]
* E_{ACC} ~ 5 MV/m acceleration field
* Limited to q/A < 1/30 or 1/60

$\Big\}$ limits

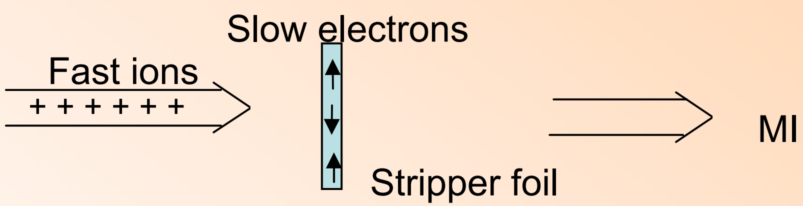
* Price for a LINAC ~0.5 MUSD/m
* Price estimate I+ acc – pure scaling

Final energy (MeV/u)	Mass (A)	Length (m)	Price (MUSD)
5	100	100	50(!)
10	100	200	100(!)

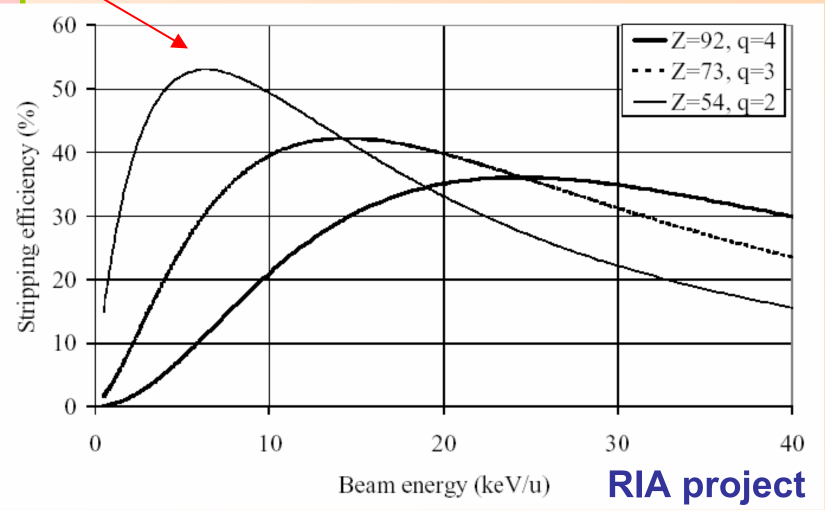


CERN proton LINAC2
* Price 38 MCHF
* Field gradient linac 1.5 – 2 MV/m
* q/A=1, 50 MeV, 34 m, 3.3 m RFQ

Classic concept – stripping



- ☺ Simple method and fast (μs isotopes)
- ☹ Needs pre-acceleration
  - in gas stripping 8 to 20 keV/u
  - in foil stripping ~0.5 MeV/u
- ☹ emittance growth (long and trans)
- 😐 no macro-bunching capability



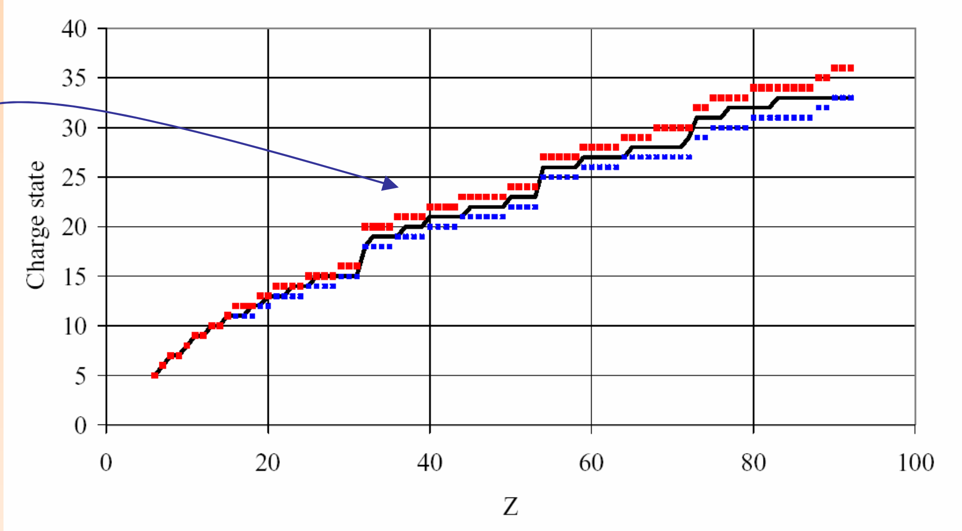
Example – SPES scenario

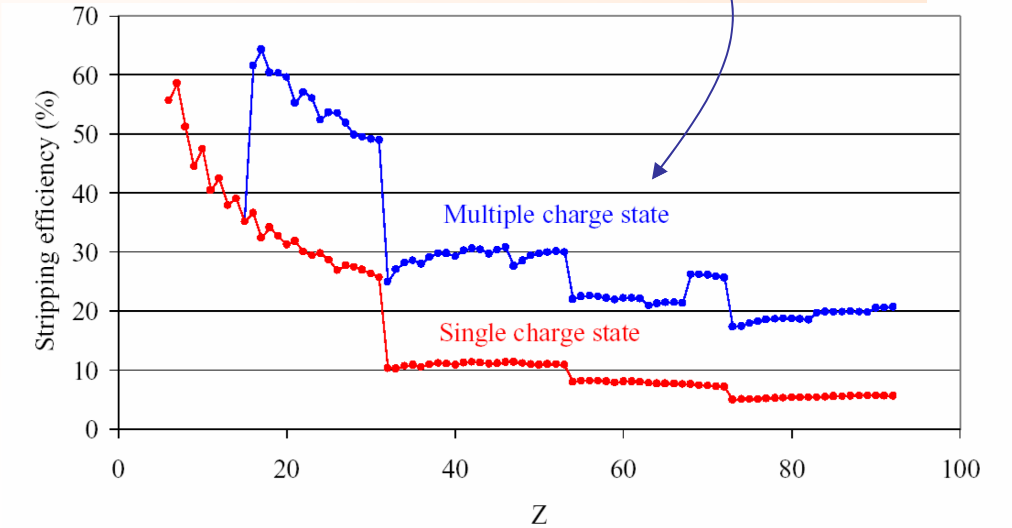
Bunching efficiency	65%
Gas stripping at 8 keV/u	40%
Stripping foil at 500 keV/u	20%
In total (single charge acc of ^{132}Sn)	4%

Multi-charge state acceleration

* Accelerate multiple q after the stripper
* $\Delta q/q$ of ~20% can be accepted

☺ Higher intensities





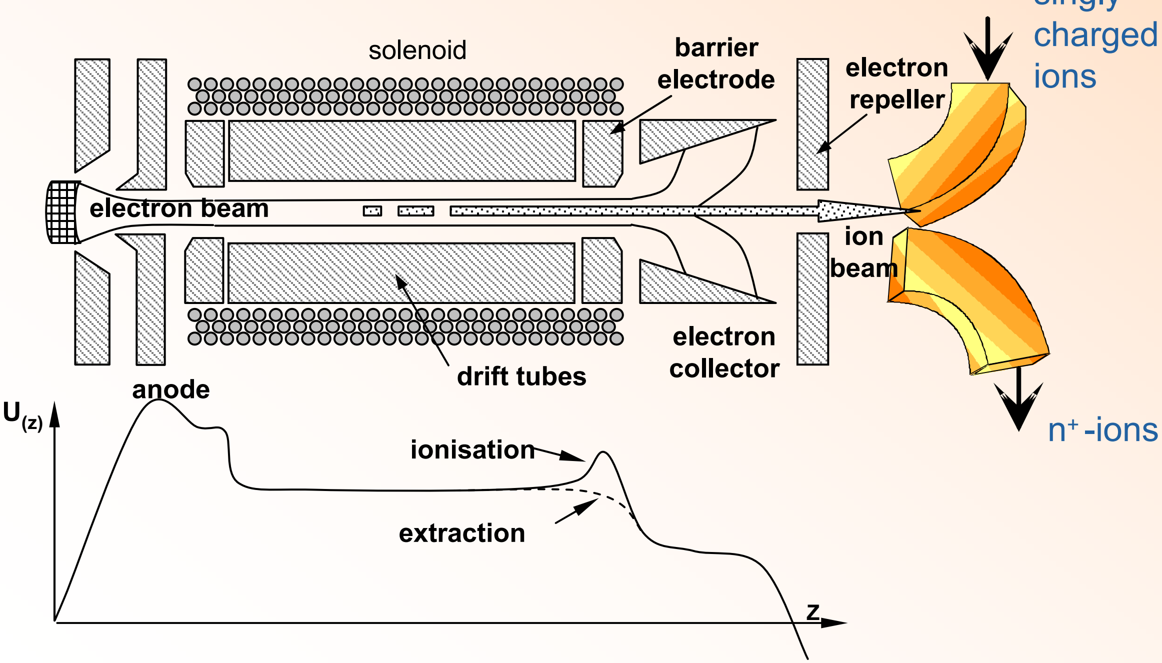
MCA and overall stripping efficiency (RIA)

☹ ε (trans. and long.) ~3 larger compared with single charge state acceleration

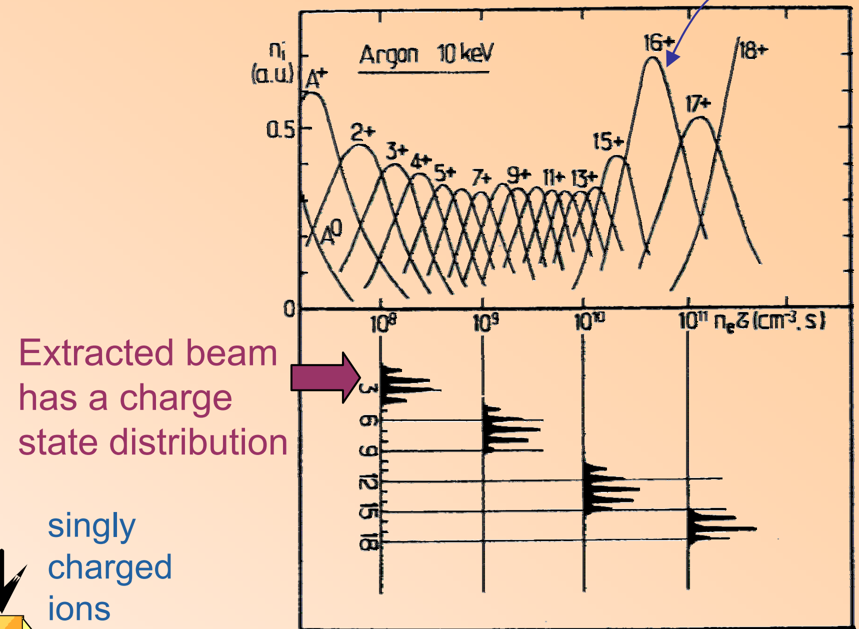
RIA project

The EBIS charge breeder

* Produces multiply charged ions
* Ions are trapped in a magneto-electrostatic trap
* Ionisation by e^- bombardment from an mono-energetic e^- beam



Electron Beam Ion Source



Charge development for stepwise ionisation

* ~25% in one charge state
* More near closed shells
* Vary $T_{breeding}$ → vary CSD

EBIS characteristics I

Breeding capacity

$$C = \frac{1.05 \cdot 10^{13} \cdot I_e L}{\sqrt{U_e}} k$$

C = number of elementary charges

I_e and U_e = e^- beam current and energy

k = neutralization factor

L = trap length

Real values

I_e = 0.5 A

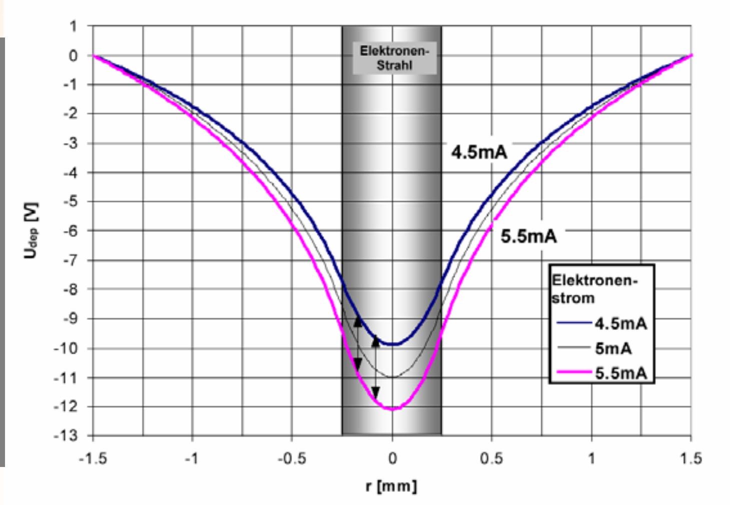
U_e = 5 000 eV

L = 0.8 m

k = 50%

⇩

~3·10[10] charges



Charge state

$$j_e \tau = \sum_{q=1}^{k-1} \frac{e}{\sigma_{q \to q+1}}$$

Typical ionization times (A/q<4.5)
(Calculated REXEBIS values)

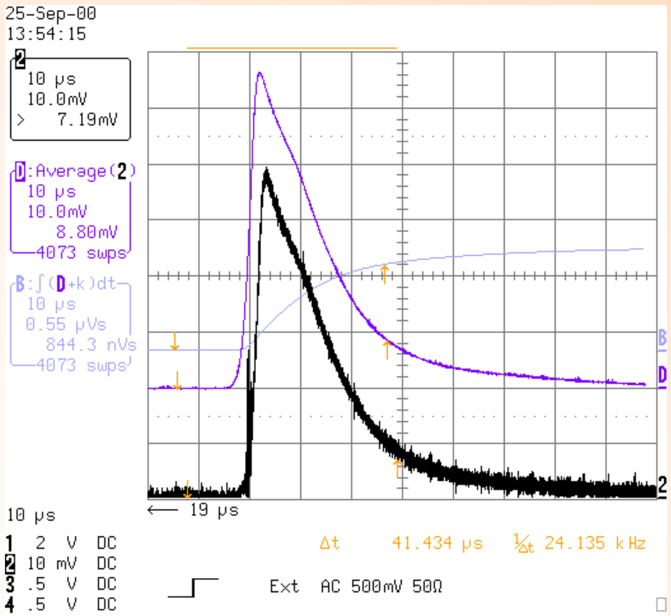
$^{52}Ca^{12+}$	20 ms
$^{70}Ni^{16+}$	22 ms
$^{78}Zn^{18+}$	30 ms
$^{86}Se^{20+}$	40 ms
$^{94}Kr^{21+}$	50 ms
$^{102}Rb^{23+}$	60 ms
$^{134}Cd^{30+}$	120 ms
$^{144}Xe^{32+}$	150 ms
$^{148}Ba^{33+}$	160 ms

☺ Short breeding time

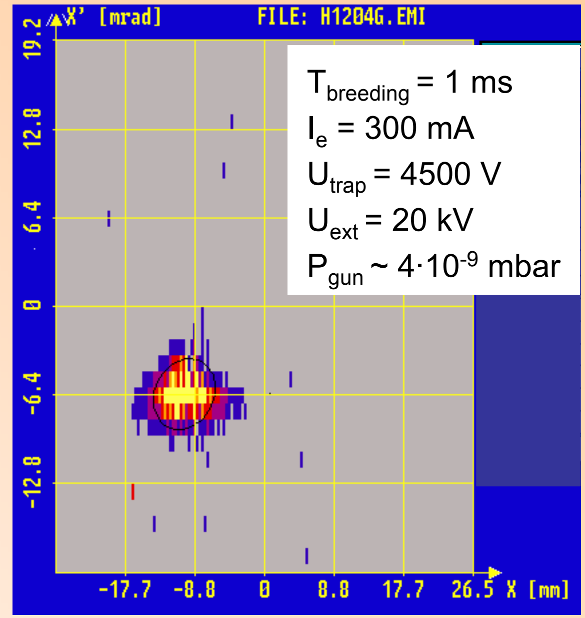
☺ Element independent

EBIS characteristics II

Time structure



Emittance / Acceptance



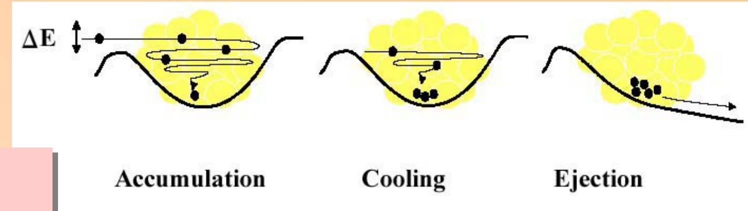
- ☹ Bunched injected beam <50 µs
- ☺ Bunched extracted beam (10 µs to several ms)
- 😐 Energy spread < 50*q eV

- ☺ Emittance
  10 π·mm·mrad (95% at 20 kV)
- ☹ Small emittance => small acceptance
  ~10 π·mm·mrad (95% at 60 kV)

* Dependent on:

Breeding time, neutralization etc

Preparatory Penning trap

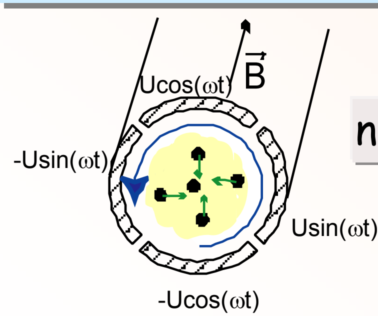


Principle
* Continuous injection
* Bunching (10-20 μs bunch extracted)
* Cooling (10-20 ms)

The large REXTRAP at ISOLDE

Results REXTRAP
(He), Li,...,U
efficiency 45 %
emittance >10 π mm mrad @ 30 keV

☹ space charge effects with sideband cooling of more than 10^5 ions/pulse
=> 10^7 ions/s



$n_B = (B^2 \varepsilon_0)/(2\ m)$

Brillouin limit

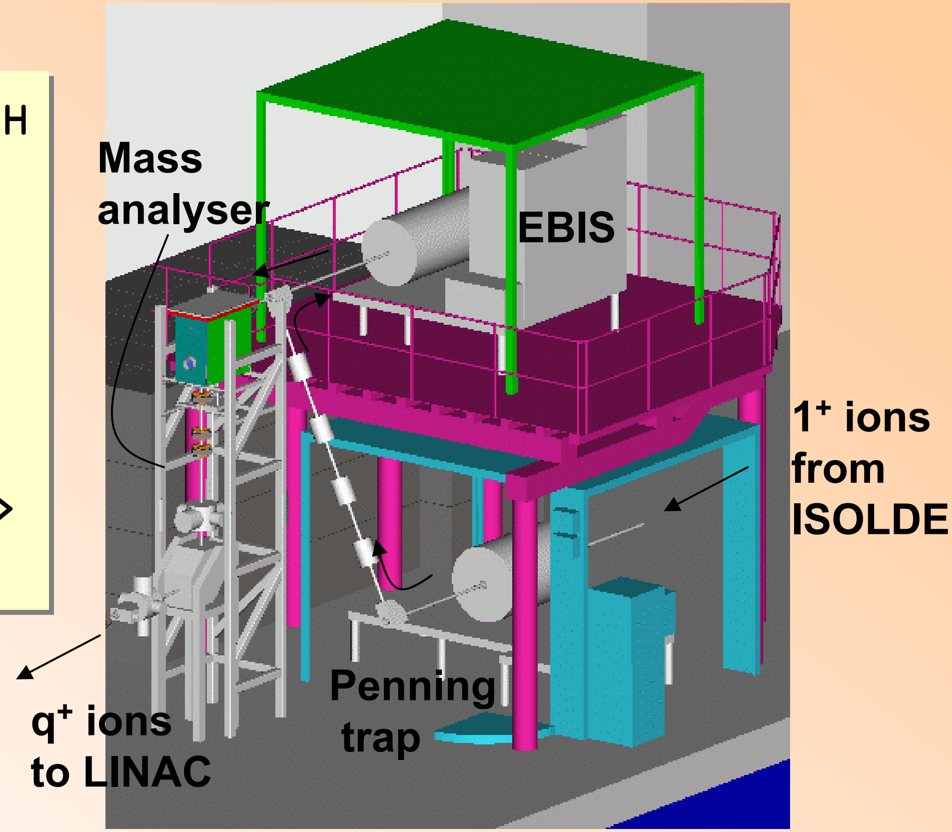
In present EBIS CB concept, trap is the limitation (10^8 ions/s)

See also P. Delahaye's poster

REX-ISOLDE bunching/cooling/breeding

* $T_{cooling}$, $T_{breeding}$ times <20 ms each
* Repetition rate up to 100 Hz
* Q/A ~ 1/4.5
* Mass separator (achromatic) resolution >100

☺ Ramp EBIS platform voltage –> decouple ISOL part and LINAC



Efficiencies (design values)

- trap bunching: 90%
- beam transport: >85%
- EBIS injection: >50%
- EBIS $Q_i/\Sigma Q_i$: 30%

$\rightarrow \Sigma_{eff}$ **12%** in one charge state

Price for EBIS and TRAP ~1.1 MUSD in total

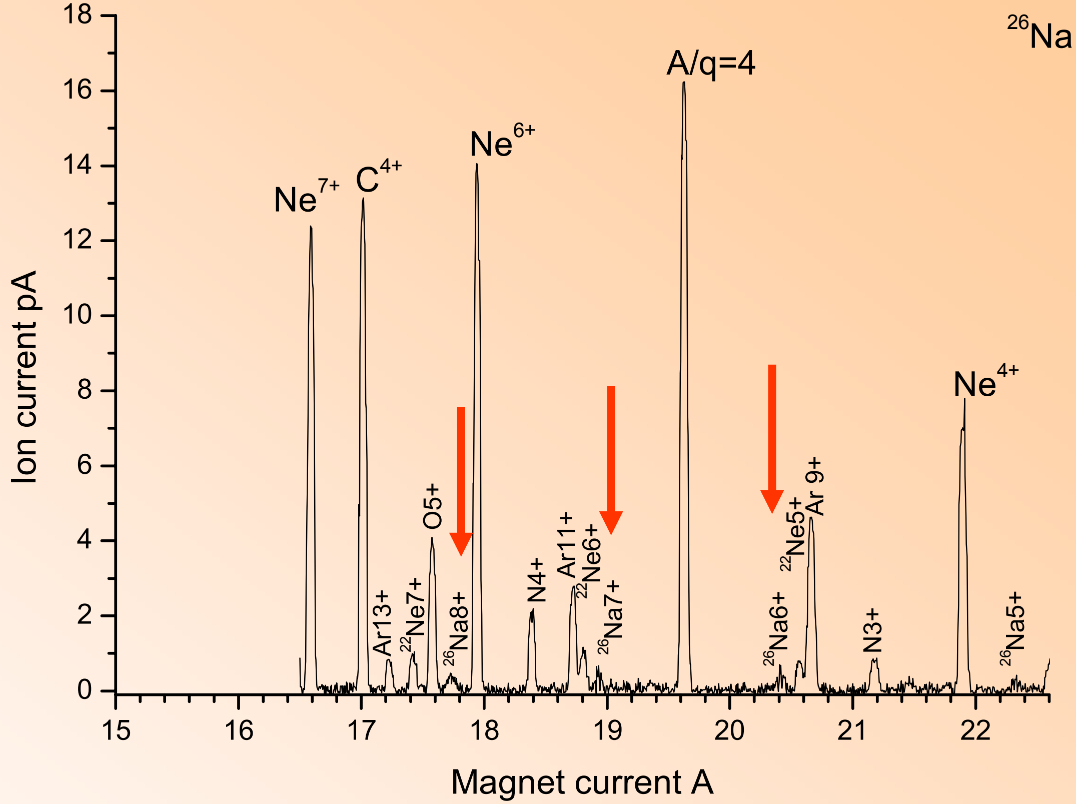
Extraction mass spectrum I

Low intensity beams

* EBIS is UHV (low residual gas, ~10^{-11} mbar)

☺ Handle fA beams

☹ Needs UHV conditions for operation



Example of beam contamination – Li run

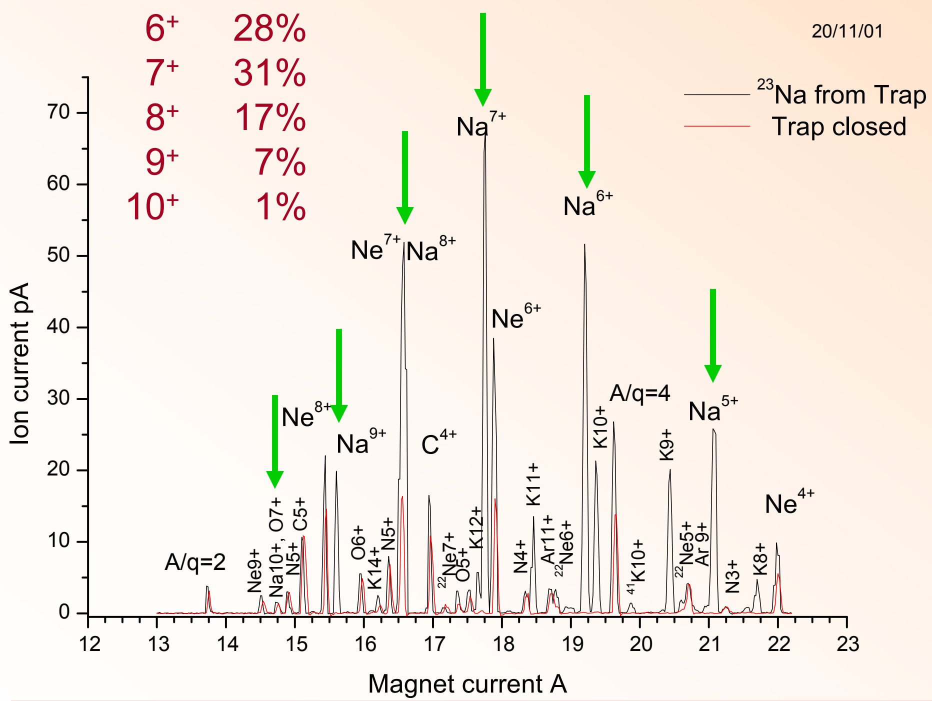
* $^{9}Li^{2+}$, run at A/q=4.5
* Contamination of $^{18}O^{4+}$ rest-gas of $1 \cdot 10^{4}$ ions/s
* Time gate => 15 times higher Li than O

Extraction mass spectrum II

* Higher intensities – >100 pA inj.
* Lower efficiency but overall more particles through

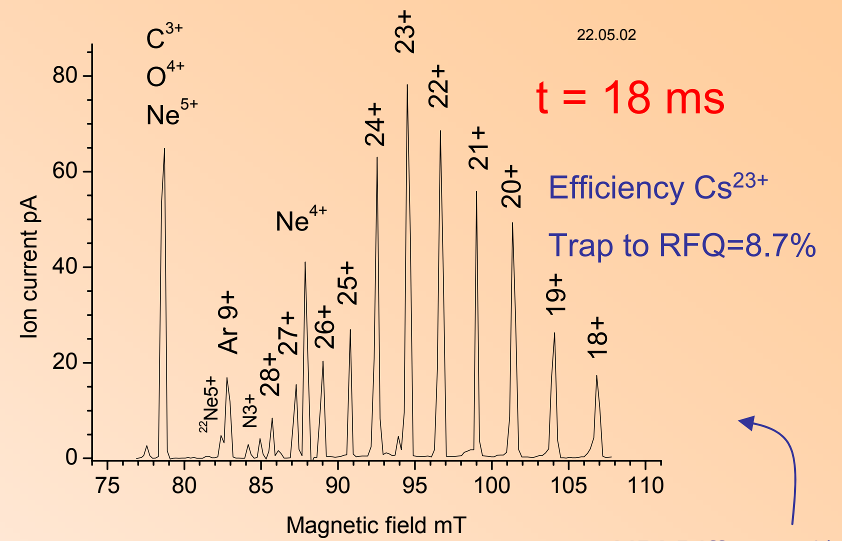
CSD

5^+	16%
6^+	28%
7^+	31%
8^+	17%
9^+	7%
10^+	1%

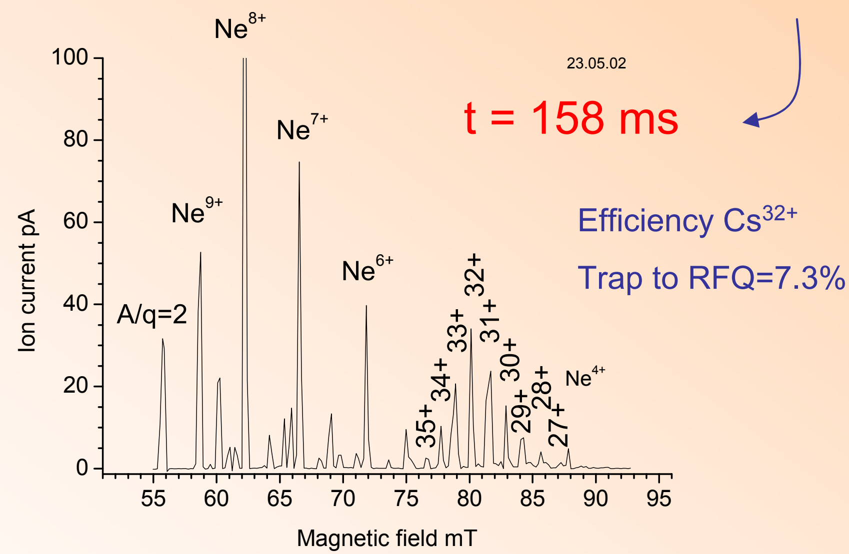


* Strong Ne contamination from trap

Vary breeding time



NB! Different 1^+ beam from trap

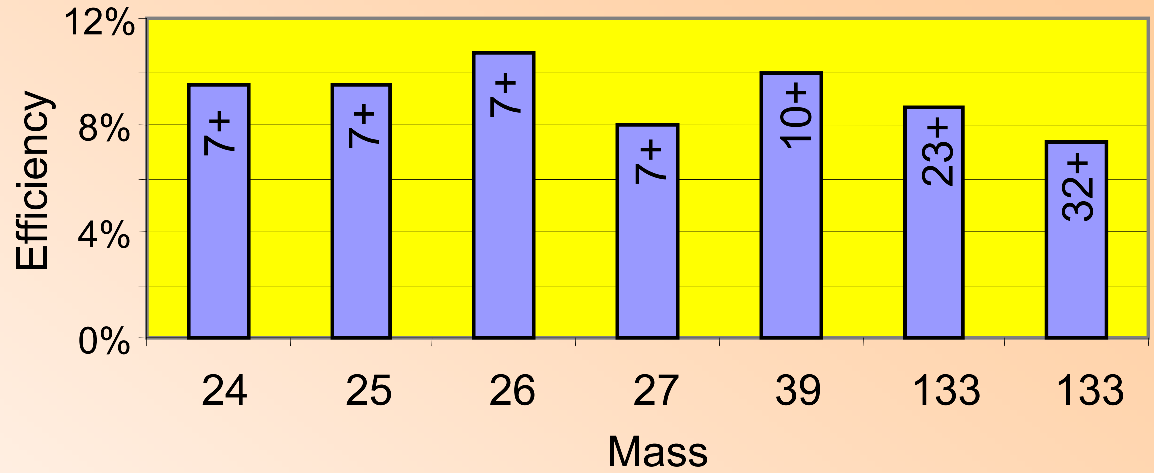


Breeding efficiency

NB! Penning trap not included!

Efficiencies

beam transport + EBIS + mass analyzer



CB in REXEBIS

Stable	Radioactive
$^{7}Li^{2+}$	$^{9}Li^{2+}$
$^{23}Na^{7+}$	$^{24-29}Na^{7+}$
$^{27}Al^{8+}$	
$^{24}Mg^{8+}$	$^{30}Mg^{8+}$
$^{39}K^{10+}$	
	$^{138}Ba^{26+}$
$^{133}Cs^{32+}$	
	$^{153}Sm^{28+}$

☺ Independent of mass

☺ Can in principle reach ~30%

(N^{7+} 30% & Ar^{14+} 9.4% in Saclay and Stockholm)

EBIS drawbacks as CB

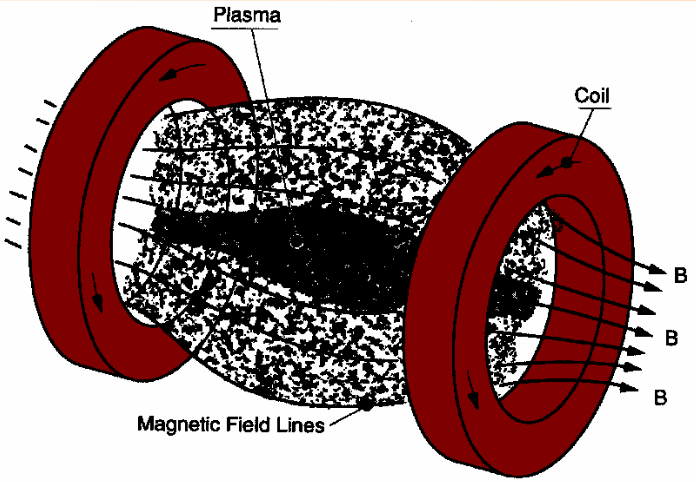
☹ Limited charge capacity

☹ Cathode limited lifetime

☹ Complicated

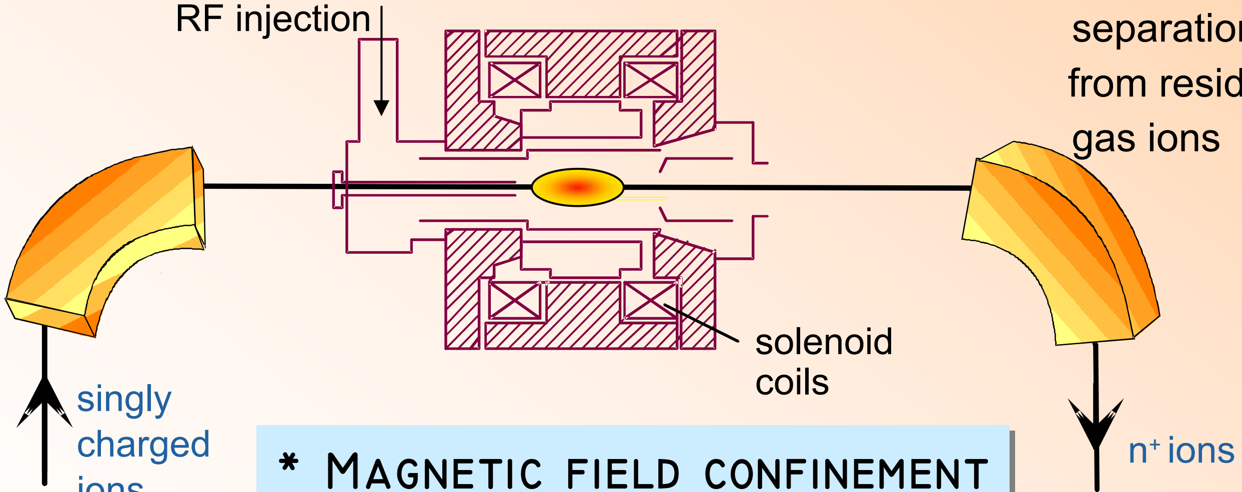
The ECRIS charge breeder

Electron Cyclotron Resonance Ion Source



Principle

* Inject very slow ions through a plasma of hot e^-
* Electron energy - a few keV
* Density $<1\cdot10^{13}$ s/cm^3
* Ionic confinement τ_i~10 ms to a few 100 ms



* Magnetic field confinement
* RF injection

Most listed ECRIS CB results are from:

LPSC Grenoble
Laboratoire de Physique Subatomique et de Cosmologie

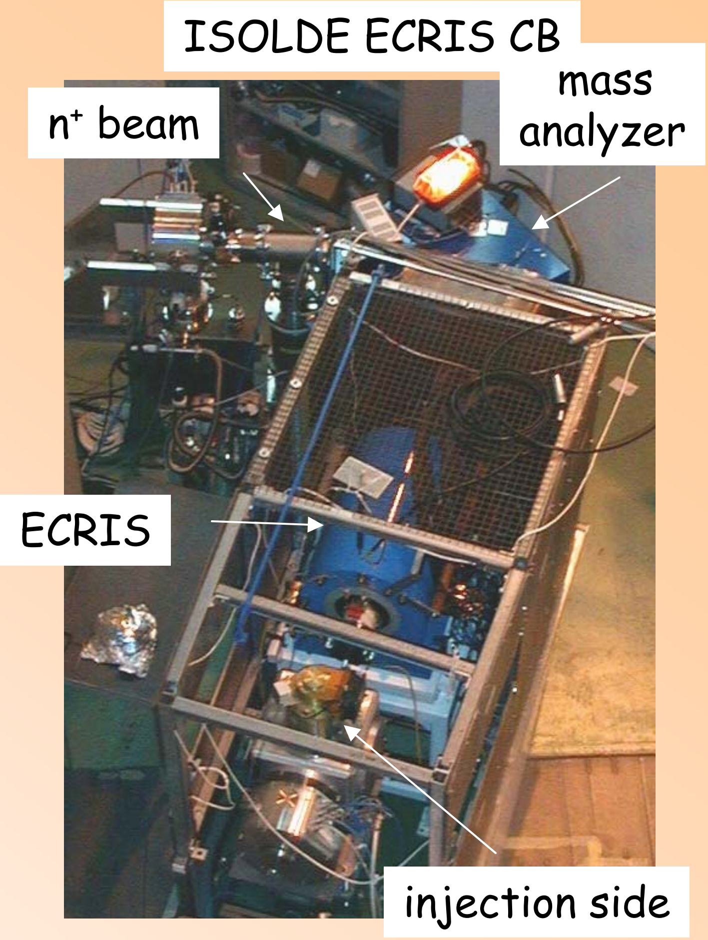
IN2P3
Institut National de Physique Nucléaire et de Physique des Particules

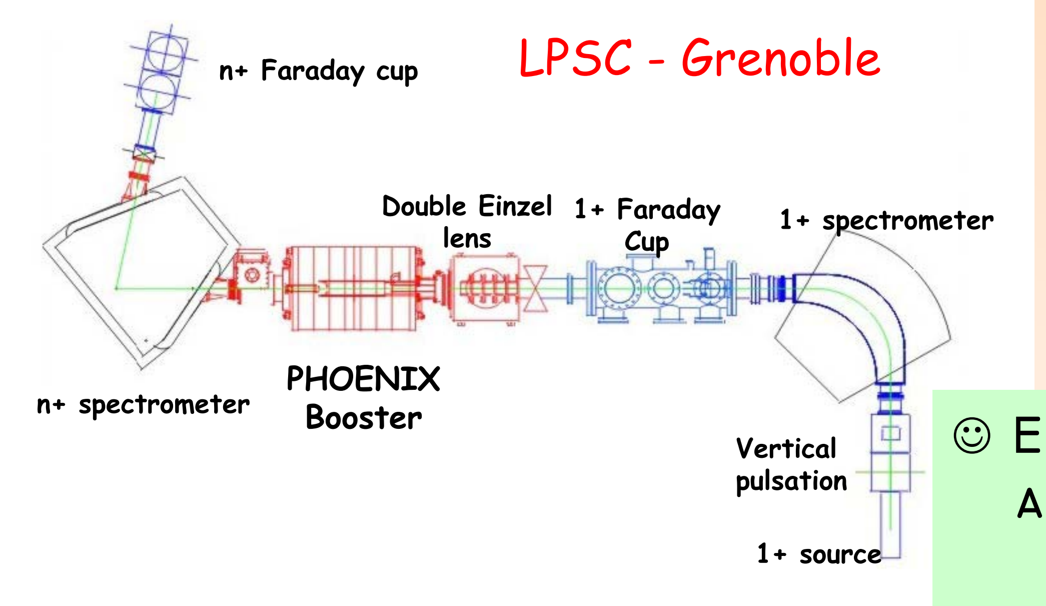
ECRIS AS CHARGE BREEDER

☺ 1^+ INJECTION CONTINUOUS OR BUNCHED

☺ NOT SO COMPLEX

* CHARGE-TO-MASS RATIO OF <1/6





☺ ECRIS MAGNETS ON GROUND => AVOID HV PLATFORM WITH 50 KW

☹ INJECTION = EXTRACTION VOLTAGE =>
- * VARY 1^+ SOURCE POTENTIAL
- * OR USE A VE-RFQ

PRICE FOR PHOENIX AND RF GENERATOR ~300 KUSD

ECRIS characteristics I

Confinement time

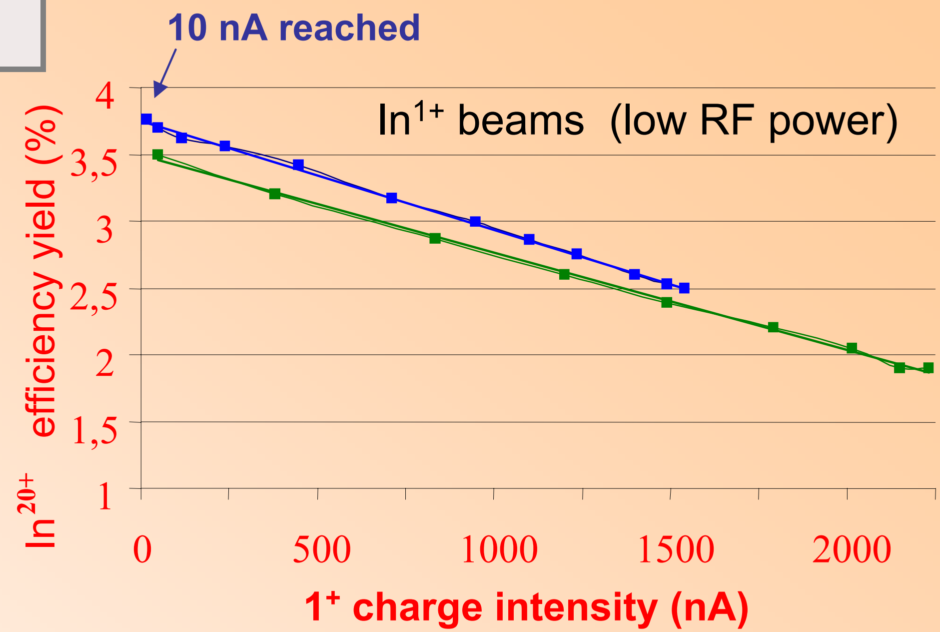
* 10 ms per charge state
* Breeding time ≠ Confinement time

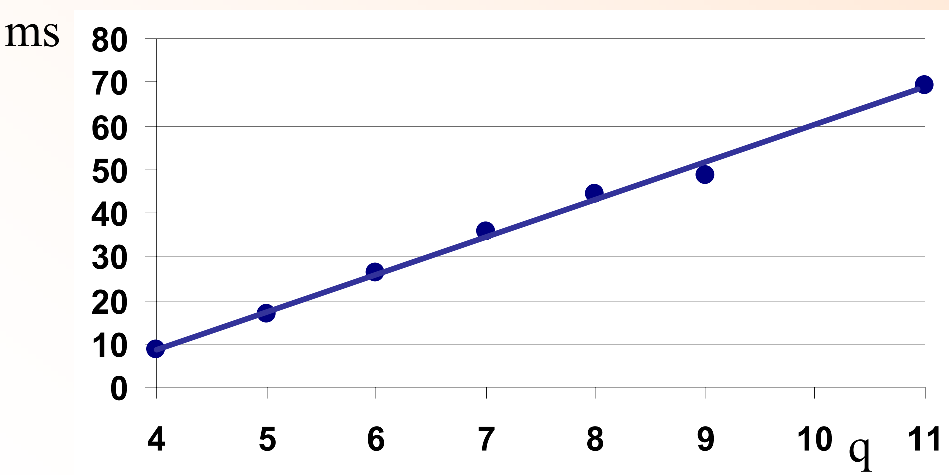
☺ Charge tuning with

RF power

magnetic field,

support gas pressure





Breeding of K in PHOENIX ECRIS

Intensity vs efficiency

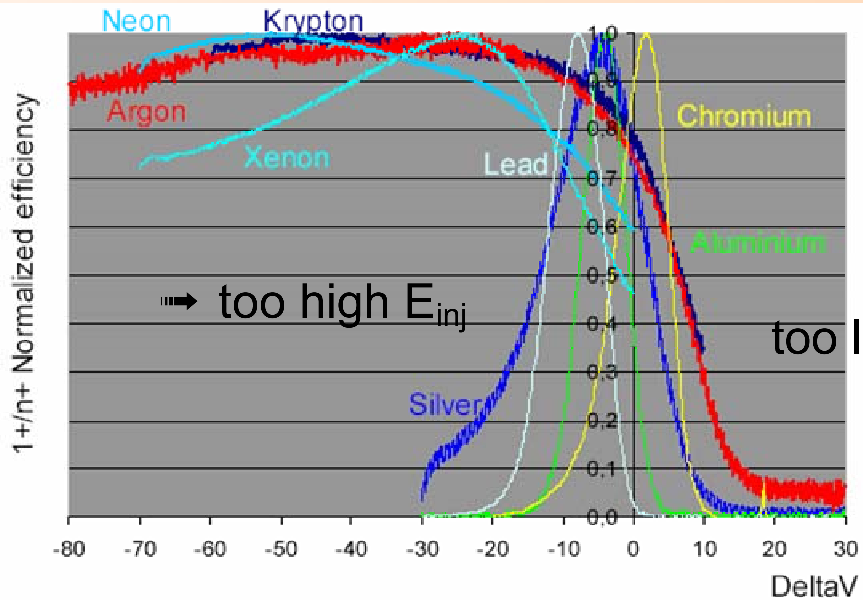
☺ No problem with 10^{12} ions/s

☺ ECRIS can accept >μA

☺ No efficiency decrease when decreasing the current

ECRIS characteristics II

Beam energies



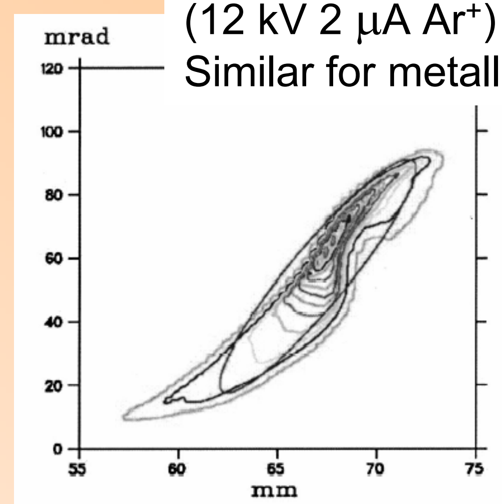
➟ too high E_{inj}

too low E_{inj} ➟

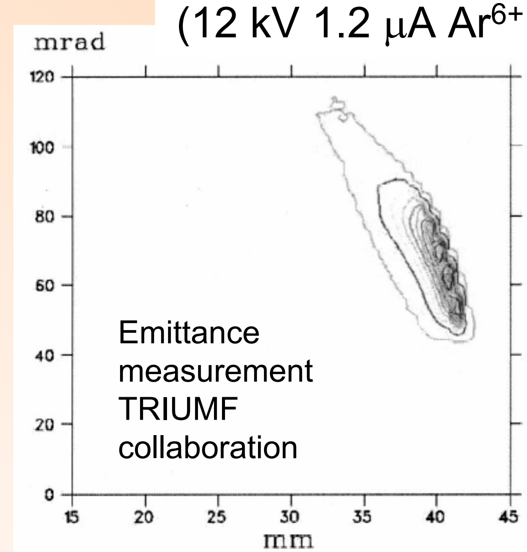
Ionization efficiency vs injection voltage

Acceptance / Emittance

α=55 π mm mrad 90%
(12 kV 2 μA Ar^{+})
Similar for metallic ions



ε=45 π mm mrad 90%
(12 kV 1.2 μA Ar^{6+})



Emittance
measurement
TRIUMF
collaboration

☹ Max ΔV for injected beam – some V

* Extracted energy spread ~ I V * q

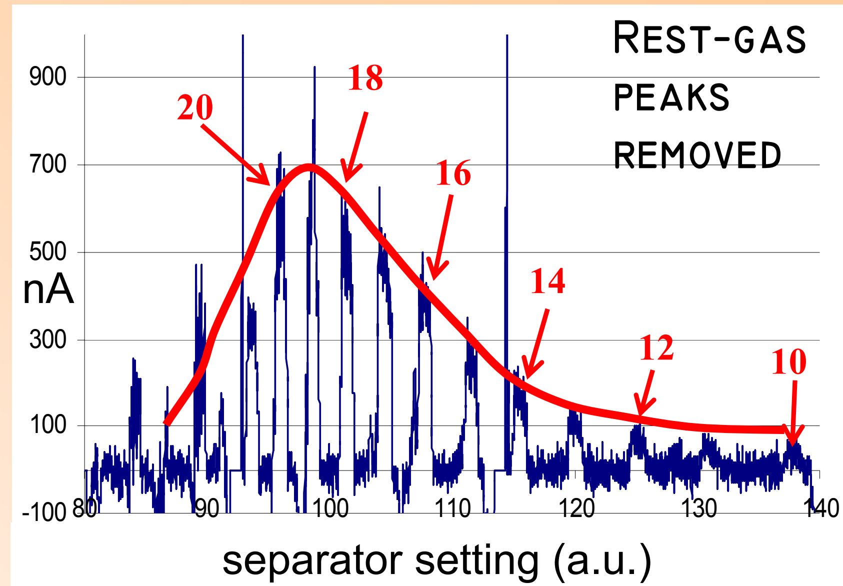
Extraction mass spectrum

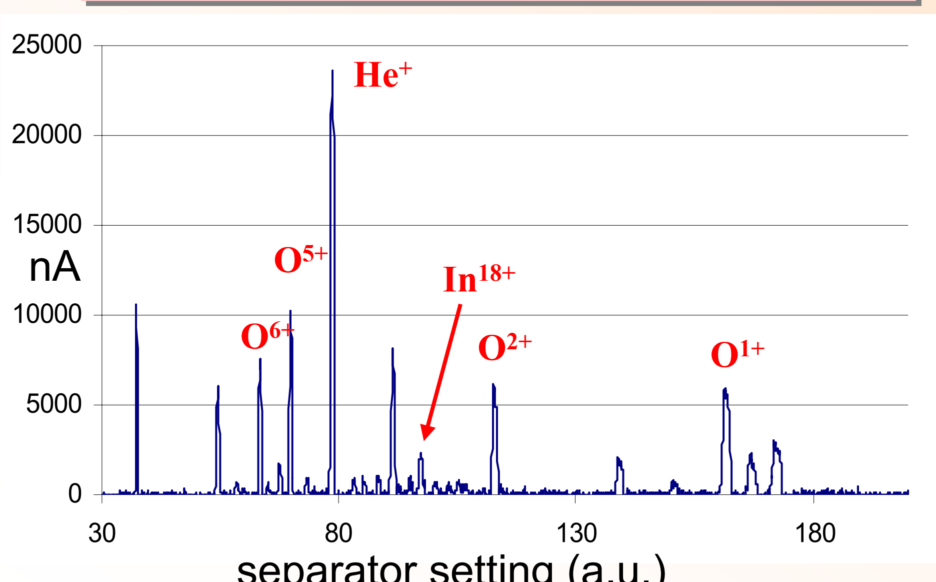
☺ High global efficiency

=> low activation

* Global capture ~50% possible (extraction in two directions)

* CSD broad due to continuous injection





Injected beam: In^{+} 520 nA, 20 KeV

RF power @ 14 GHz: 340 W

Total HV current: 1.1 mA

* $\eta(1^{+} \rightarrow 18^{+})$ = **6%**
* Global capture = **45%**

Residual gas background

😐 Total extracted current 1-2 mA

* Working pressure = 1 to $10 \cdot 10^{-6}$ mbar
* Residual gas peaks >> radioactive atoms

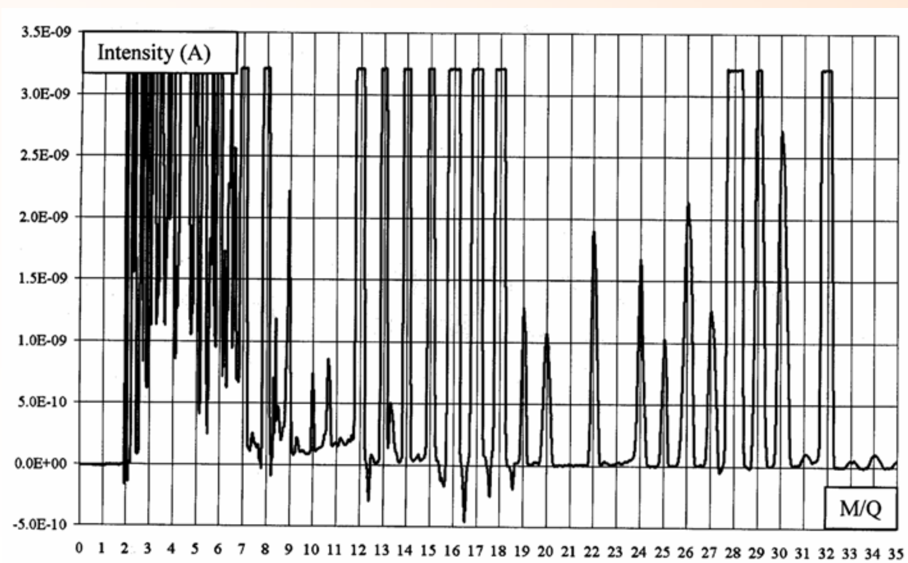
Noise level in between residual gas peaks?

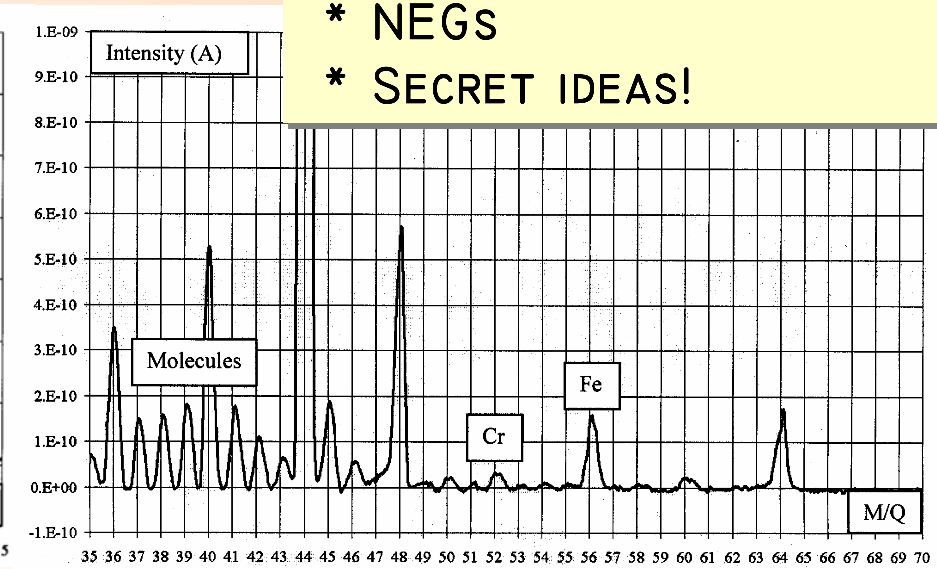
* KEK-JAERI has 10 nA in 6<A/q<7

Residual gas suppression

* Wien filter
* bakeable UHV devices?
* monoisotopic buffer gas
* NEGs
* Secret ideas!

* Non UHV PHOENIX booster spectrum, A/q=0-70





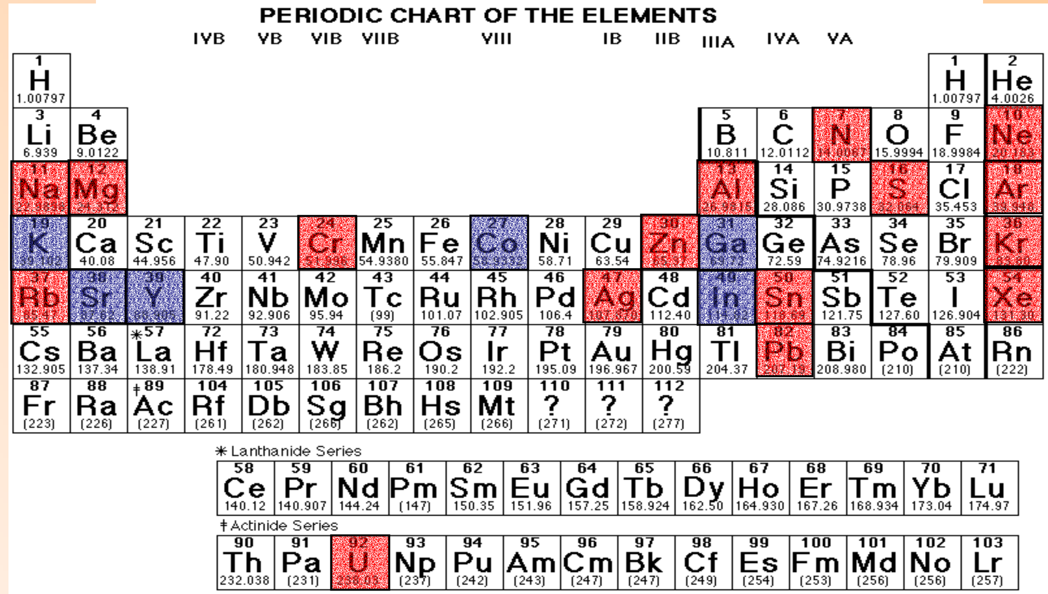
Produced elements

☺ Works for any element and any I^+ source

☺ Fast setup: different stable beam within an hour

* Easiest
  - Noble gases
  - Heavier elements

Elements which have been experimentally studied with the ISN-ECRIS charge breeder



Institut des Sciences Nucléaires de Grenoble

TRIUMF-Vancouver / IN2P3-ISN Collaboration

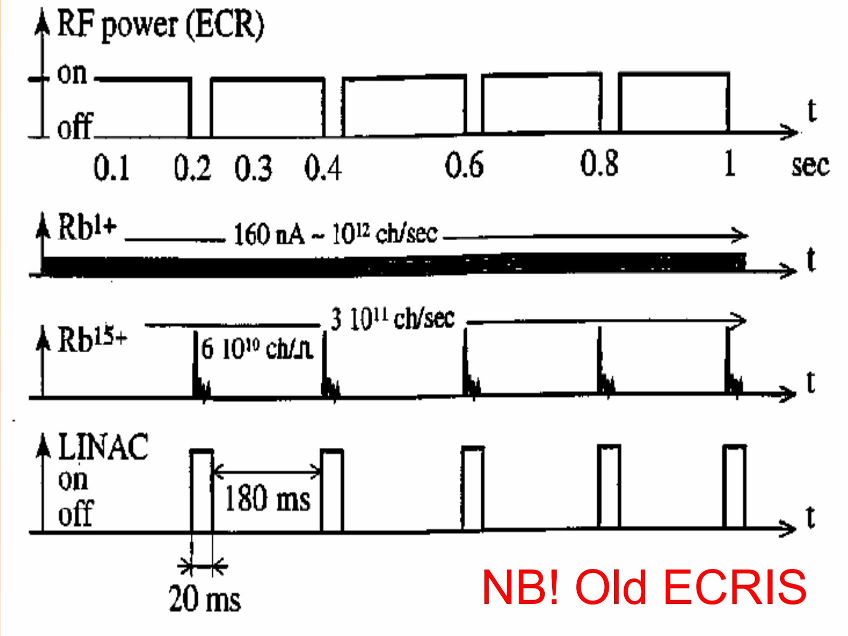
* "Daily production" of $A/q \approx 7$
* Elements produced in ~10 days:

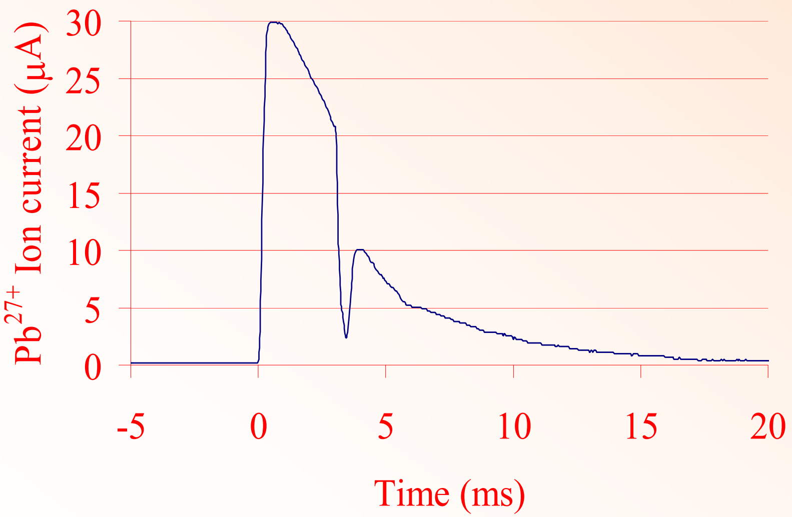
^{115}In, ^{109}Ag, ^{64}Zn, ^{120}Sn, ^{88}Sr, ^{69}Ga, ^{90}Y, ^{39}K, ^{85}Rb, ^{59}Co

* Charge breeding efficiency of at least 3%

Pulsed extraction

* Extraction CW or afterglow pulsed
* Afterglow method = switch off RF
* Pulsed extraction for synchrotrons and pulsed linacs





Typical afterglow signal for charge bred Pb^{27+}

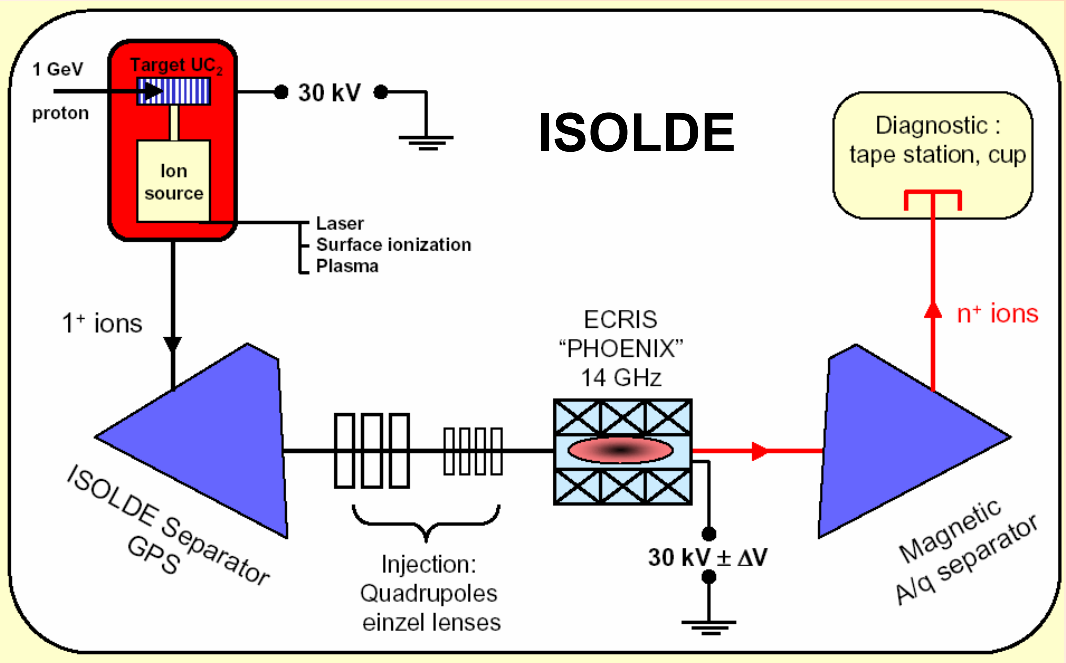
CB with afterglow extraction

* Beam in Rb^{1+}
* Beam out Rb^{15+}
  $6 \cdot 10^{10}$ charges/pulse
  $3 \cdot 10^{11}$ charges/s

  2.2 % efficiency

ECRIS CBs around the world

Comparison ECRIS and REXEBIS at ISOLDE



* From 10 to 18 GHz (28 GHz possible)
* modular axial B-field

Results from KEK-JAERI

* 18 GHz ECRIS, A/Q<7
* 6.5% breeding efficiency Xe^+ to Xe^{20+}

* ISAC (TRIUMF) has also a PHOENIX under commissioning

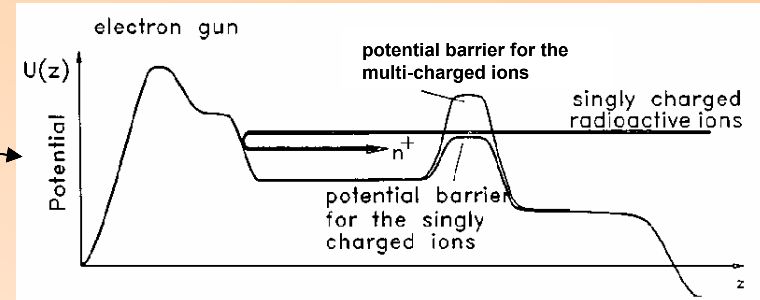
Future EBIS

Goal of 5 ms (1000 A/cm^2 Dubna) ⇨

* Repetition rate 200 Hz
* No life-time losses at
* High capacity

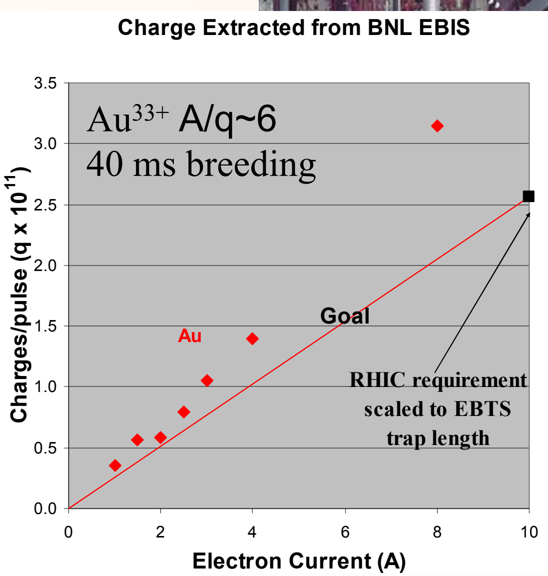
What to improve on EBIS?

1. Shortening of the $T_{BREEDING}$
2. Continuous injection
3. Increased charge capacity

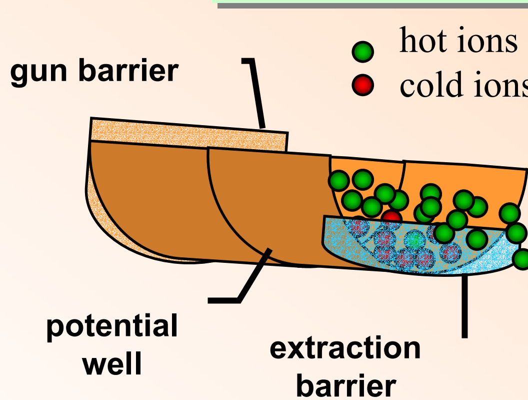


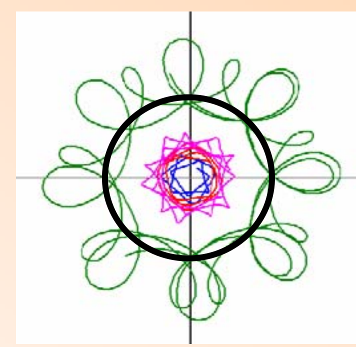
Continuous injection / Accu EBIS with RFQ cooler

EBIS test stand



Advanced charge breeding





RF excitation

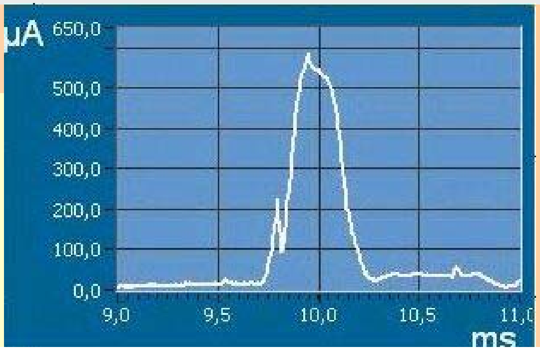
Trends in ECRIS development

* Shorter extraction pulse

* Shorter confinement time
  Modular ECRIS

* Higher charge state / larger capacity / better I^+ capture
  Higher RF frequency
  $n_E \propto \omega_{RF}^2$ (scaling rule)
  $B_{RESONANCE} \sim \omega_{RF}$ -> high B-field and SC solenoids

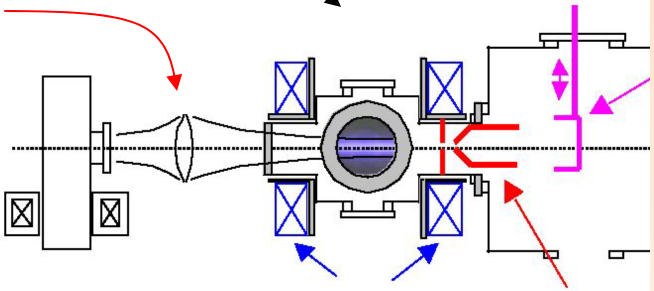
PHOENIX 28 GHz
high current extraction (Lead)

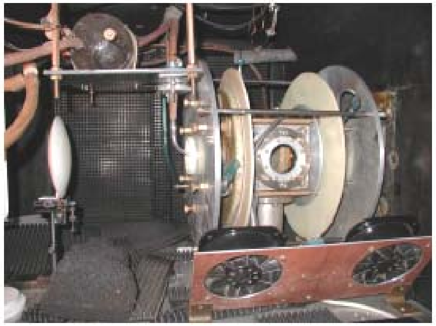


Shorter and higher afterglow

Optical coupling of the UHF power :
* < **100 KW** / 1 ms each 20 s
* ω_{RF} = 37.5 GHz

Very simple magnetic system

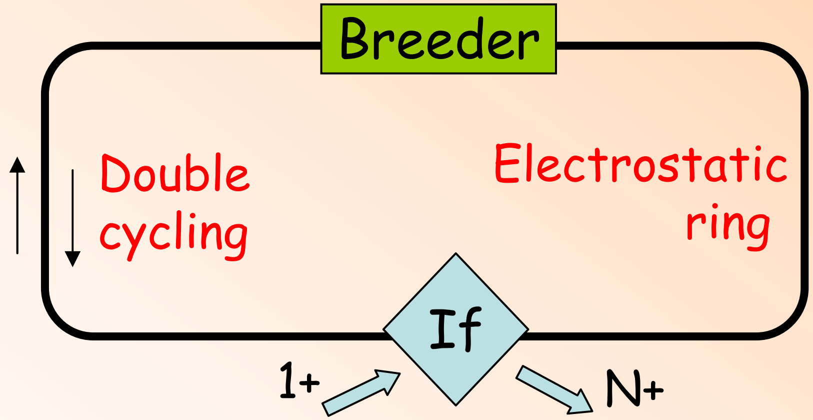




$n_e \sim 5 \cdot 10^{13}$ cm^{-3}

IAP Nizhny Novgorod + LPSC

Breeder ring



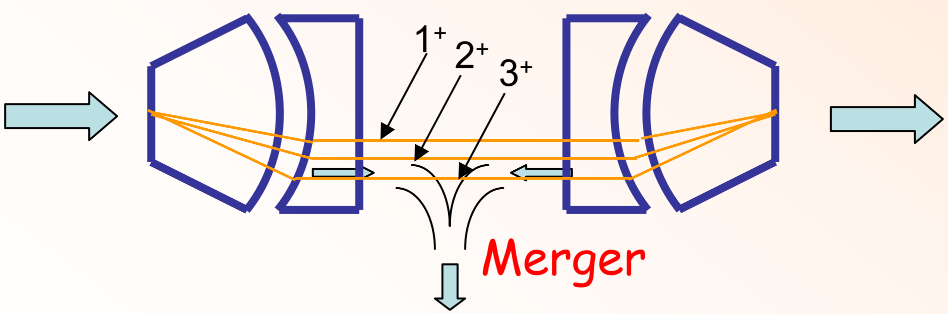
Operation efficiency

I_∞ = na/[1-μ(1-a)]
n=extraction eff.
a=ionisation eff.
μ=ring transport eff.

NB! Decay losses excluded.

Example: n=0.9, a=0.8, μ=0.9 => **0.87**

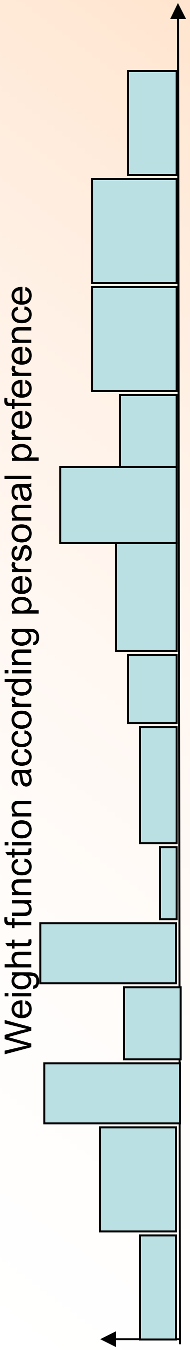
Large dispersive magnetic separator/merger



Problems

* added delay time
* transport losses
* extraction/injection losses

Idea from E. A. Lamzin, Russia
Pursued by A. Villari and GANIL



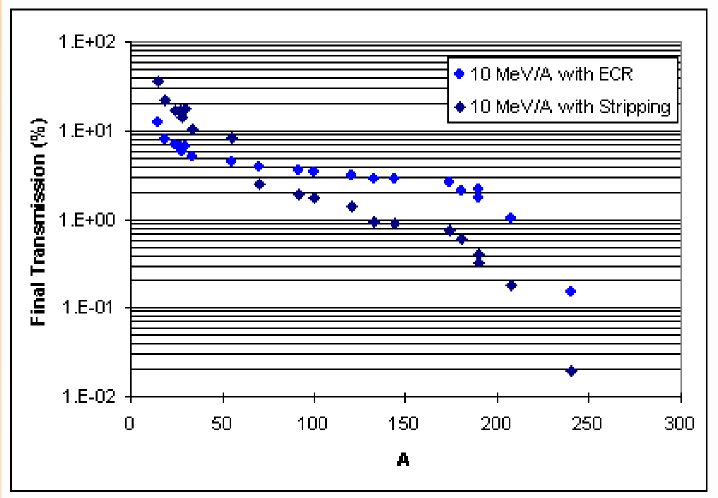
	Stripper	EBIS	ECRIS
Simplicity	3, passive element	1, complicated (SC, UHV, e-gun)	2, medium (RF, beam tuning)
Beam properties in	3, no special requirements	1, bunched, small acceptance	2, CW, medium acceptance
Beam properties out	1, emittance blow-up	3, us or ms bunch, small emittance	2, CW or bunched
Low intensities	3, no contamination	2, some 100 fA	1, high rest-gas level
Rapidity	3, instant, us isotopes	2, 10 ms	1, a few 10 ms
CSD	3, narrow, high charge state	3, narrow, high charge state	2, broad CSD, moderate charge
CSD tuning	1, not tunable	3, change time	2, many parameters
Machine contamination	2, foil change	1, multiple parts	2, change plasma liner
Storage time	1, non existing	3, up to s	2, ~100 ms
Beam capacity	3, very high, 100 uA	1, limited to nA	2, several uA
Energy spread	1, $\Delta W/W$~1‰	2, a few 10 eV*q	3, some eV*q
Efficiency	2, a few %	2, a few %	2, a few %
Life-time	2, foil breakage, 50 mC/cm^2	1, electron cathode	3, klystron lifetime
Price	1 high, (incl. pre-acc)	2 ~1 MUSD (trap +EBIS)	3, ~0.3 MUSD

Conclusions

Guidelines

* Obtained CB efficiencies in 5% region
* EBIS for low intensities
* ECRIS-stripper combination for high intensities

Breaking point 1 nA



Transmission efficiencies
for ECR and stripping schemes

Three choices - three virtues

Stripper

Fast but expensive

(pre-acc. LINAC)

ECRIS

Large capacity but dirty

EBIS

Electrical car

Clean but low capacity

* Future interesting concepts
* Advanced charge breeding proposal

Acknowledgement

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